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COMPUTATION OF RESIDUAL STRESSES DUE TO PHASE
TRANSFORMATIONS DURING QUEN. (U) ARMY CLOSE COMBAT

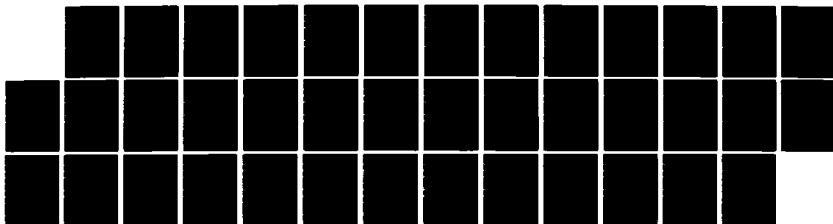
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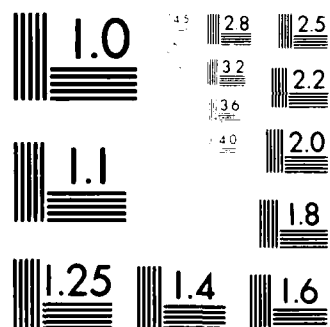
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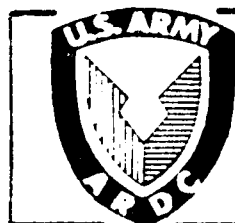
TECHNICAL REPORT ARCCB-TR-86024

AD-A170 493

COMPUTATION OF RESIDUAL STRESSES DUE TO PHASE TRANSFORMATIONS DURING QUENCHING OF HOLLOW CYLINDERS

J. D. VASILAKIS

JULY 1986



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In a previous paper, a method for computing the stresses due to the combined effects of transient temperatures and material phase transformations was described. The general purpose finite element program ADINAT/ADINA was used for the computation of both the transient temperatures and the associated stresses. The problem considered was that of an axisymmetric hollow cylinder undergoing a water-spray quench. The present work considers a similar model, (CONT'D ON REVERSE)		

20. ABSTRACT (CONT'D)

but is better able to describe the residual stress state because of the availability of a more accurate set of properties for the material expansion due to the phase transformation. Effects on the transient and residual stresses due to modifications of the material expansion and varying quench rates are discussed.

It was found that the stresses due to the transformation are more severe than those due to the transient temperatures alone. Inelastic behavior is found to occur in all the cases considered and high residual stresses can exist on the inner and outer surfaces. While dependent on actual material composition, these residual stresses can lead to quench cracking.

The model describes the rapid quenching of steel gun tubes for the purpose of developing a martensitic grain structure and desired physical properties in the tube.

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INTRODUCTION

Rapid quenching of components from initially high temperatures usually results in development of residual stresses within the components upon cooling. The quenching is normally undertaken to develop a desired microstructure in the material which would determine its behavior or response in use. These changes in microstructure, or transformations, cause volume changes which can give rise to stresses in the component in addition to the stresses due to the rapid temperature changes. Thus, the residual state of stress which exists when the component is cooled to room temperature is due to the combined effect of transient temperatures and material phase transformation.

In a previous paper (ref 1), a method for computing the stresses due to these combined effects was described. The general purpose finite element program ADINAT/ADINA was used for the computation of both the transient temperatures and the associated stresses. The problem considered was that of an axisymmetric hollow cylinder undergoing a water-spray quench. The present work considers a similar model but is better able to describe the residual stress state because of the availability of a more accurate set of properties for the material expansion due to the phase transformation. The material properties and system parameters used in the computations, such as quenching time, were chosen using the rotary forge quench facility at Watervliet Arsenal as a model.

The quench facility has nozzles on several diametral planes for spraying

¹J. D. Vasilakis, "Thermal and Transformation Stresses in Hollow Tubes During the Quenching Process," Transactions of the First Army Conference on Applied Mathematics and Computing, ARO Report 84-1.

water on the outer diameter of a long tube as it is slowly rotated. The bore, or inner surface of the tube, can also be cooled by a bore flush. There have been several types of quench cycles in the past. These include varying quench times of the outer diameter for the breech and muzzle ends of the tube. The long tubes are usually of constant bore diameter and varying outer diameter with the larger being the breech end and the smaller the muzzle end. Quenching of the bore can be omitted, delayed, or simultaneous with the outer diameter quench, etc. The goal was to develop the design properties in the tube without causing quench cracking due to the high residual tensile stresses at the bore.

Since the diameter of these tubes varies slowly, end effects are ignored and the tube is treated as a long axisymmetric cylinder. In the earlier work (ref 1), the transient temperatures and combined stresses for the breech and muzzle ends were treated as two separate cases. This earlier work also considered the effects of the different quench cycles. The geometry used is that of the muzzle or smaller end of the long tube. It is also assumed that no bore quench takes place. This was done because most of the quenching currently being undertaken at the facility does not use the bore quench. Latent heat is ignored in the computation of the transient temperatures. This is not due to a limitation of the model, but to a lack of appropriate input.

Based on recent experimental work (ref 2), the residual stresses can now be computed from realistic temperature-transformation curves. Also, because

¹J. D. Vasilakis, "Thermal and Transformation Stresses in Hollow Tubes During the Quenching Process," Transactions of the First Army Conference on Applied Mathematics and Computing, ARO Report 84-1.

²P. Cote, Private Communication, Benet Weapons Laboratory, September 1984.

of information on the martensite transformation itself, the effect of new quench cycles on the cooling curves can be seen. The resultant residual stress distributions can then be discussed.

PROBLEM STATEMENT

Thermal and transformation stresses are computed for long hollow cylinders as they are being quenched. The effects due to the transient temperature distributions and the martensite transformation are both considered in the stress calculations. The thermo-physical properties are assumed to be temperature dependent. The residual stress distributions at the end of the quench cycles are presented. Both experimentally developed and assumed transformation-temperature curves are used, and the quench cycle is varied. A general purpose finite element program ADINAT/ADINA is used for the computations.

FINITE ELEMENT PROGRAM

The finite element geometry for the problem is shown in Figure 1, along with a simplified drawing of a gun tube. Eight node quadrilateral elements are used in the model. The present work shows results only for the muzzle end of the tube. In the earlier work (ref 1), stress and temperature results for the breech end of the tube due to different quench cycles and an assumed transformation-temperature curve were presented.

¹J. D. Vasilakis, "Thermal and Transformation Stresses in Hollow Tubes During the Quenching Process," Transactions of the First Army Conference on Applied Mathematics and Computing, ARO Report 84-1.

The finite element program actually consists of two parts, one for computing temperatures, ADINAT, and one for computing stresses, ADINA. Each program can stand alone, but when one wishes to compute thermal stresses using the same geometry, ADINAT produces a file which includes the temperatures at the node for each time step if the problem is a transient one. This ADINAT output file can then be used as input to ADINA for the stress computation.

In the program, the thermo-physical properties were considered as functions of temperature. The convection losses during the heat transfer portion of the computation are considered to be due to the temperature difference between the tube wall and ambient, which is assumed to be 13.3°C (65°F). For the computation of stresses, one has a choice of several material behavior models in ADINA. The one chosen for this work was Model 10 (ref 3) which is applicable to the thermo-elastic-plastic solution of interest. The yield criterion assumed was the distortion energy criterion and the yield stress was assumed to be a function of temperature. No creep or hardening was assumed although the model allowed both to be incorporated.

To compute thermal stresses, the problem for the transient temperatures was solved using just ADINAT as indicated above. The special file created by ADINAT was then used as input to ADINA to compute the thermal stresses. However, in many cases in solving the temperature problem, time increments vary. Short-time increments are used during periods of large transients, and longer-time increments when the temperature gradients are not as severe.

³M. Snyder and K.-J. Bathe, "Formulation and Numerical Solution of Thermo-Elastic-Plastic and Creep Problems," NTIS: PB-274-044, June 1977.

While ADINAT allows one to change time increments, ADINA does not. This difficulty was overcome by manipulating the temperature file used for stress computation so that with the restart capability, ADINA would see only one time increment during any one computation interval. Finally, the restart facility in ADINA (ref 4) was altered so that a restart could be undertaken from any previous time instead of just the last completed step.

The computation of transformation stresses and combined thermal and transformation stresses can be treated like thermal stresses with little additional effort. The effect of the transformation, at least the aspect of it giving rise to stresses, is to create a volume change in the material. In this case the volume change is an increase, and it occurs when the temperature at a point in the material becomes equal to the martensite start (M_s) temperature and is completed when it reaches the martensite finish (M_f) temperature. If the transformation is assumed to be isotropic, then the linear expansion can be taken as one-third the volume change. Reference 1 describes what was done when the expansion due to the volume change was available as a separate quantity from the thermal expansion coefficient of the material. The current work takes advantage of the fact that the expansion is available from experiments as the combined effect.

¹J. D. Vasilakis, "Thermal and Transformation Stresses in Hollow Tubes During the Quenching Process," Transactions of the First Army Conference on Applied Mathematics and Computing, ARO Report 84-1.

⁴Fred Gregory, Private Communication, Ballistics Research Laboratory, April 1983.

EXPERIMENTAL WORK

Cote (ref 2) is conducting tests on various steels used in the manufacture of large caliber cannon. Small samples of the steels are quenched at different rates and the expansion in each sample is determined. He supplied the data for the experimental curve for the linear expansion versus temperature curve shown in Figure 2. He also suggested the modified curve as being typical of another type of steel or one in which some bainite has formed in addition to martensite. Other aspects of his work indicate that the desired microstructure can be achieved with slower quench cycles. This work has guided some of the decisions as to what quench cycles to run, what transformation curves to use, etc.

RESULTS AND DISCUSSION OF RESULTS

The early work (ref 1) was based on the assumed transformation-temperature curve shown in Figure 2. The experimental curve was not available at that time. Based on that curve, however, several different quench cycles were run to determine the transient temperature distributions and the associated residual stresses. The quench cycles previously run were:

1. Bore quench started at the same time as the outside diameter (OD) quench.
2. Bore quench started 30 seconds before the OD quench began.
3. Bore quench started 30 seconds after the OD quench began.
4. No bore quench.

¹I. D. Vasilakis, "Thermal and Transformation Stresses in Hollow Tubes During the Quenching Process," Transactions of the First Army Conference on Applied Mathematics and Computing, ARO Report 84-1.

²P. Cote, Private Communication, Benet Weapons Laboratory, September 1984.

These were run for both the muzzle and the breech end of the gun tube. For comparison purposes, some of this earlier work is shown in Figures 3 through 5. The results are for the muzzle end with no bore quench taking place. Figure 3 shows the variation with time of the tangential stress at the bore and in the outer surface. Since this was a four-minute quench simulation, the stresses at time 250 seconds are the residual stresses at those respective points. The breaks in the curves indicate when the phase transformation would begin and end in the bore and on the outer surface. The onset of inelastic deformation can also be found as can changes in the slope of the phase transformation-temperature curve. Figure 4 shows the residual stress distribution throughout the cylinder wall. High compressive stresses are seen at the bore and high tensile stresses are seen on the outer surface. Figure 5 is a series of figures showing the tangential stress distribution across the wall thickness at different times. The transformation started on the outer diameter by 150.5 seconds and continued into the cylinder. It began on the inner diameter (ID) by 175.5 seconds and the residual stress state (similar to Figure 4) is seen at time 245.5 seconds.

The results for other transformation curves in Figure 2 are shown in the remaining figures. The phase transformation curves used here for the computation of residual stresses are the experimentally determined one and the one modified from it. In addition, each was run with a fast quench (~ 4 minutes) and a slow quench (~ 15 minute) cycle. Boundary conditions for the computation of temperatures are not readily available. The only known information is that the temperature on the muzzle end of the tube reaches about 200°F in approximately four minutes. This point is about eight minutes

on the breech end. A constant convection coefficient, h , is found by exercising the program which gives us this point and is used in subsequent runs. The geometry for the muzzle end was used and no bore quench was considered. Figures 6 through 9 represent the transient temperatures experienced by the tube during quenching. Figure 6 is the response of the fast quench and the temperature distribution throughout the wall at selected times is shown. The effect on the temperature distribution due to the OD quench only is easily seen, especially at early times. The difference between the outer diameter and bore diameter temperatures at any time is found in Figure 7, again for the fast quench cycle. Figures 8 and 9 show the thermal results for the slow quench cycle, with Figure 8 showing the radial distribution of temperatures, and Figure 9 the OD and ID temperature as they vary in time. It is easily seen that the temperature difference between the ID and OD is much less during the slow quench.

Figures 10 and 11 show some of the stress results due to the experimental phase transformation curve and a fast quench cycle. This is perhaps the worst case as far as high stress gradients and residual stresses are concerned. The distribution of tangential stresses throughout the wall is shown in Figure 10 for specific times. At time 121 seconds the transformation began on the OD, and at time 150 seconds it began on the ID. The effect on the stresses is due primarily to the volume change associated with the transformation. This can easily be seen by considering the stresses prior to the transformation beginning and the changes to the state of stress after it has been completed. Figure 11 shows the fluctuation of the stresses at the ID and OD of the tube throughout this quench cycle. Again the breaks in the curve are due to the

onset of transformations, the onset of inelastic material behavior, and changes in slope of the transformation curve. High tensile stresses are found at the bore. Figures 12 and 13 show the results for the experimental transformation curve and the slow quench. Since it was thought that the desired material microstructure would be developed even during a slow quench for a specific steel, the combination of loads was run. From Figure 12 one can see that the initial thermal stresses are small, as the thermal gradients are much less during the slower quench. The transformation on the OD started about 460-470 seconds into the run, and on the ID probably about 40-50 seconds later. The residual state of stress is shown at the end of the quench cycle. High residual stresses are found at both the ID and OD but do not appear to penetrate into the interior of the tube section as they did during the rapid quench cycle. Bore tangential stress, however, is still tensile. Figure 14 shows the history of the tangential stress at the bore and OD. Most of the action occurs during the period from 450-625 seconds when the material is undergoing the transformation.

By subjecting the material to more time at the austenitizing temperature or perhaps by changing the austenitizing temperature, it may be possible to change the shape of the phase transformation-temperature curve. For this reason, it was decided to look at the type of results that would arise if the modified transformation curve in Figure 2 was used. Figures 14 and 15 show the results for this curve with the first quench cycle. While the high stresses do occur on the ID and OD, the penetration of these stresses into the interior is not as much as it was with the experimentally determined transformation curve. Figures 16 and 17 depict the results for the modified

transformation curve and slow quench. In this case, the residual stresses are small.

CONCLUSIONS

Using experimental results as a guide, this work looked at the residual stress states in a long hollow tube which arise when the cylinder is quenched. These stresses are due to the transient temperatures during quenching and the material transformation that occurs. High tensile stresses occurred at the bore for all runs. These are the stresses that can lead to quench cracking.

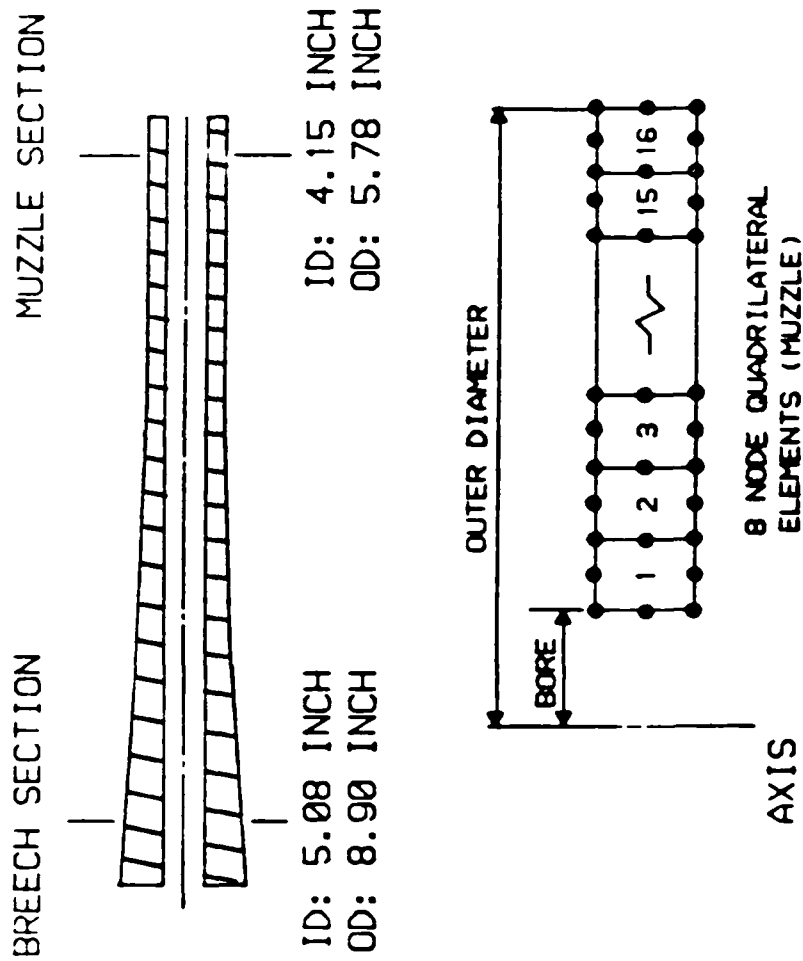
In all runs, the stresses that occurred due to the phase change were much more severe than those due to the thermal gradients. During the slow quench, the thermal stresses were very small by comparison. For the more rapid quench, although more severe, they still were much less than the transformation stress. One should recall that the cylinder modeled is a steel one and the thermal conductivity is high tending to keep the gradients small. Varying the quench cycle, e.g., introducing bore quench, would not significantly change the stresses due to the temperature gradients alone.

The stresses due to the transformation cause inelastic material behavior, almost from the time the transformation begins. At the higher temperatures, it is expected that yielding could occur without generating cracks due to a more ductile response. A slow quench with the experimentally determined transformation curve or either the slow or the fast quench with the modified transformation curve show more shallow areas on the ID and OD for high residual stresses. Less material is thus subject to high stresses. Although this analysis cannot predict the onset of cracks due to quenching, it tends to

indicate that fast quench and experimental transformation curve would have a higher propensity for cracking. Either modifying the transformation curve or slowing the quench would help decrease the possibility of quench cracking.

REFERENCES

1. J. D. Vasilakis, "Thermal and Transformation Stresses in Hollow Tubes During the Quenching Process," Transactions of the First Army Conference on Applied Mathematics and Computing, ARO Report 84-1.
2. P. Cote, Private Communication, Benet Weapons Laboratory, September 1984.
3. M. Snyder and K.-J. Bathe, "Formulation and Numerical Solution of Thermo-Elastic-Plastic and Creep Problems," NTIS: PB-274-044, June 1977.
4. Fred Gregory, Private Communication, Ballistics Research Laboratory, April 1983.



PROBLEM GEOMETRY

FIGURE 1.

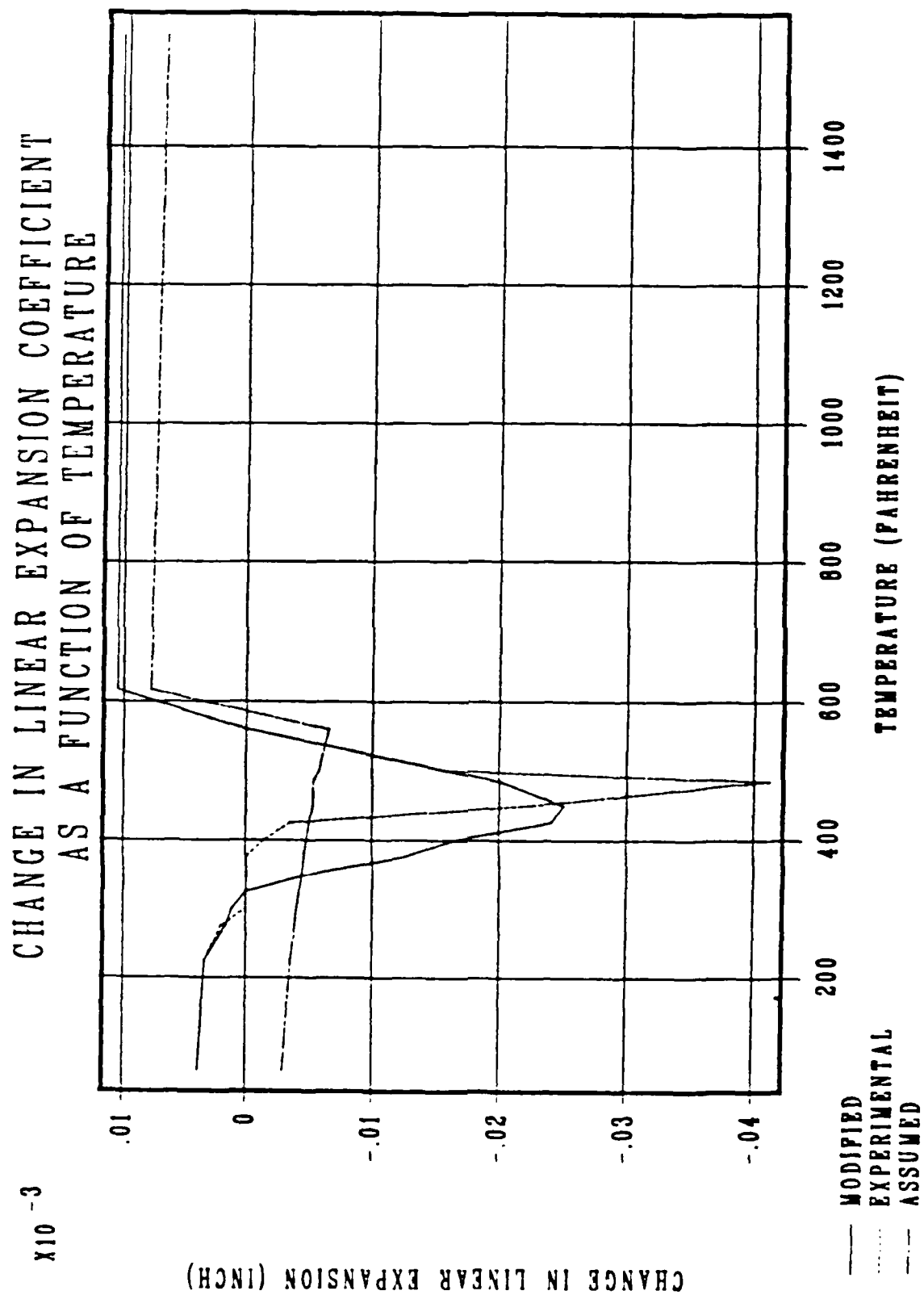


FIGURE 2.

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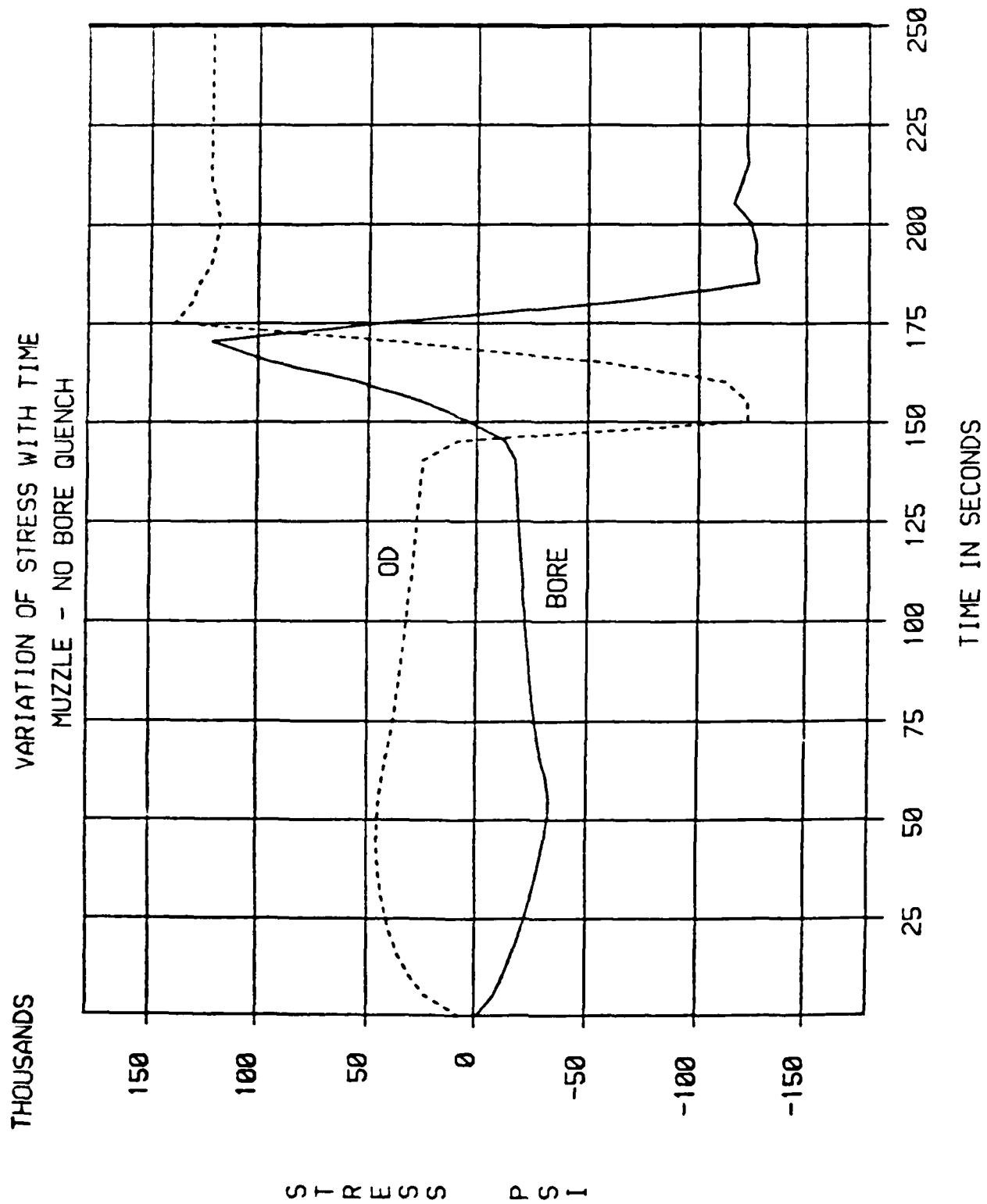
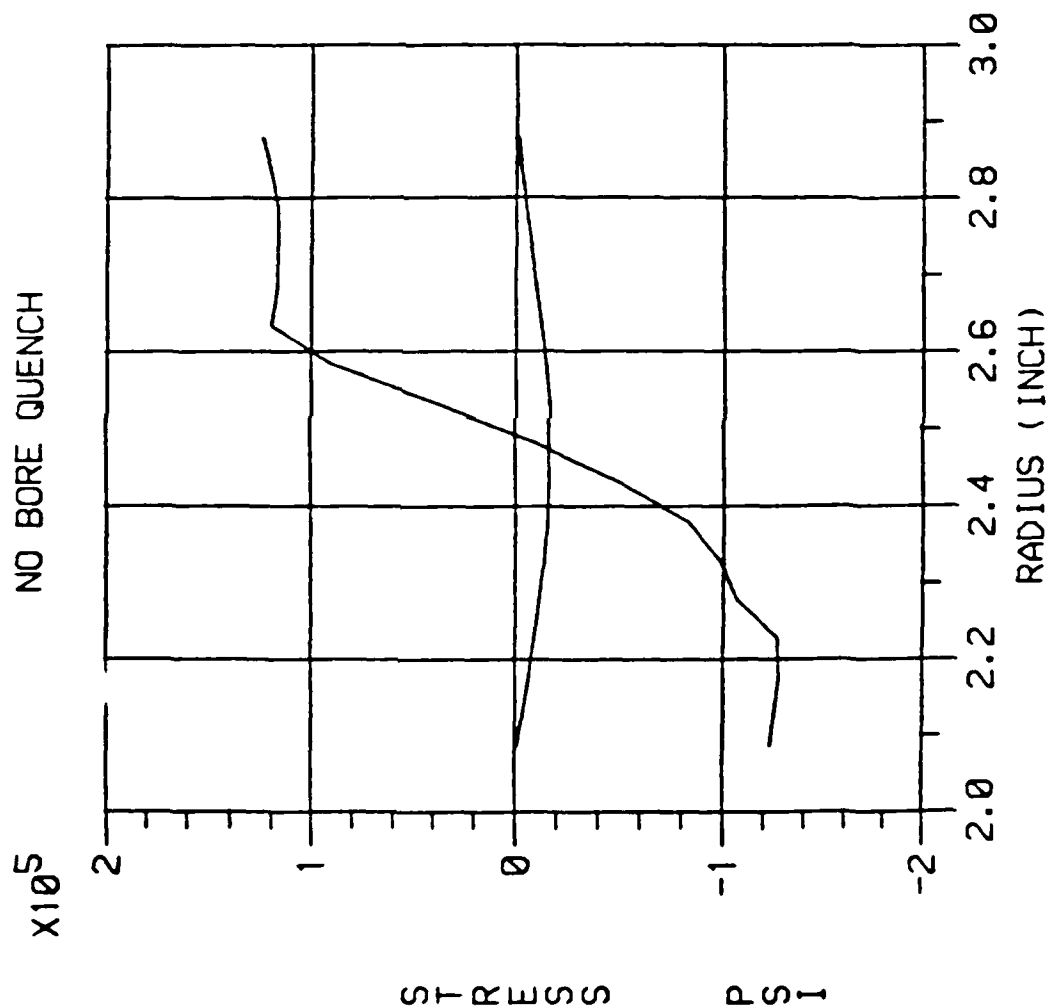


FIGURE 3.

THERMAL AND TRANSFORMATION STRESS
NO BORE QUENCH



MUZZLE END
YIELD .. 160 KSI
TIME 250.500

MS = 617 F
MF = 500 F

FIGURE 4.

TANGENTIAL STRESS vs RADIUS DURING QUENCH
 ASSUMED EXPANSION CURVE

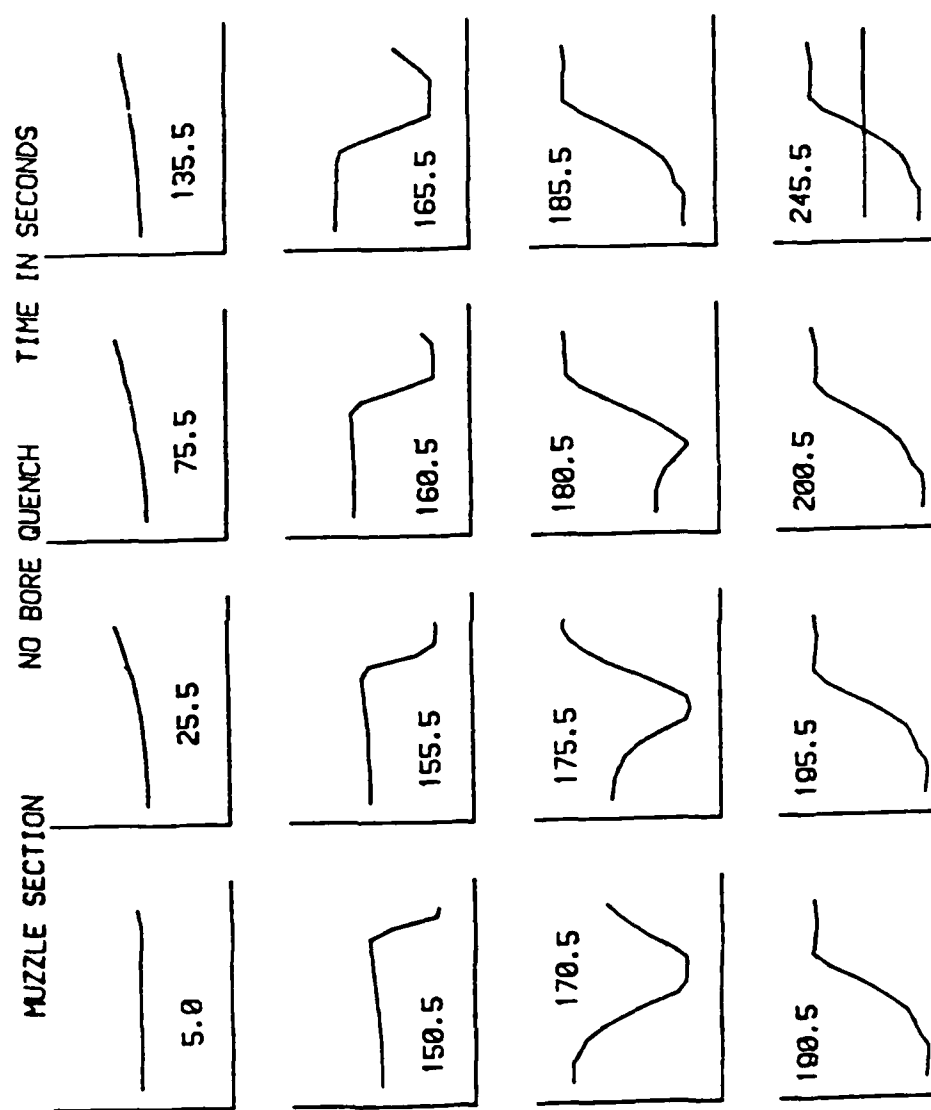


FIGURE 5.

TRANSIENT TEMPERATURES IN TUBE DURING QUENCH

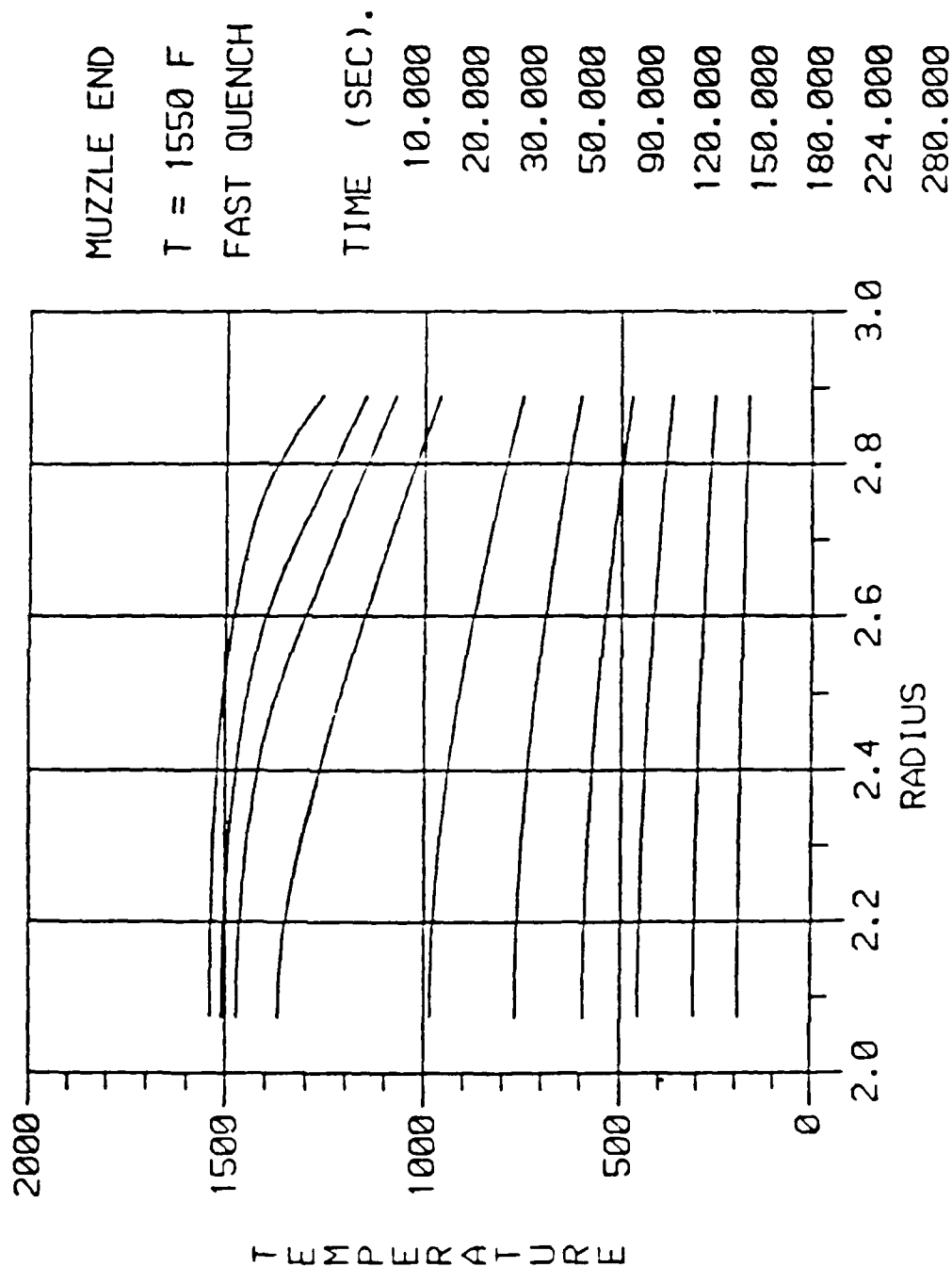
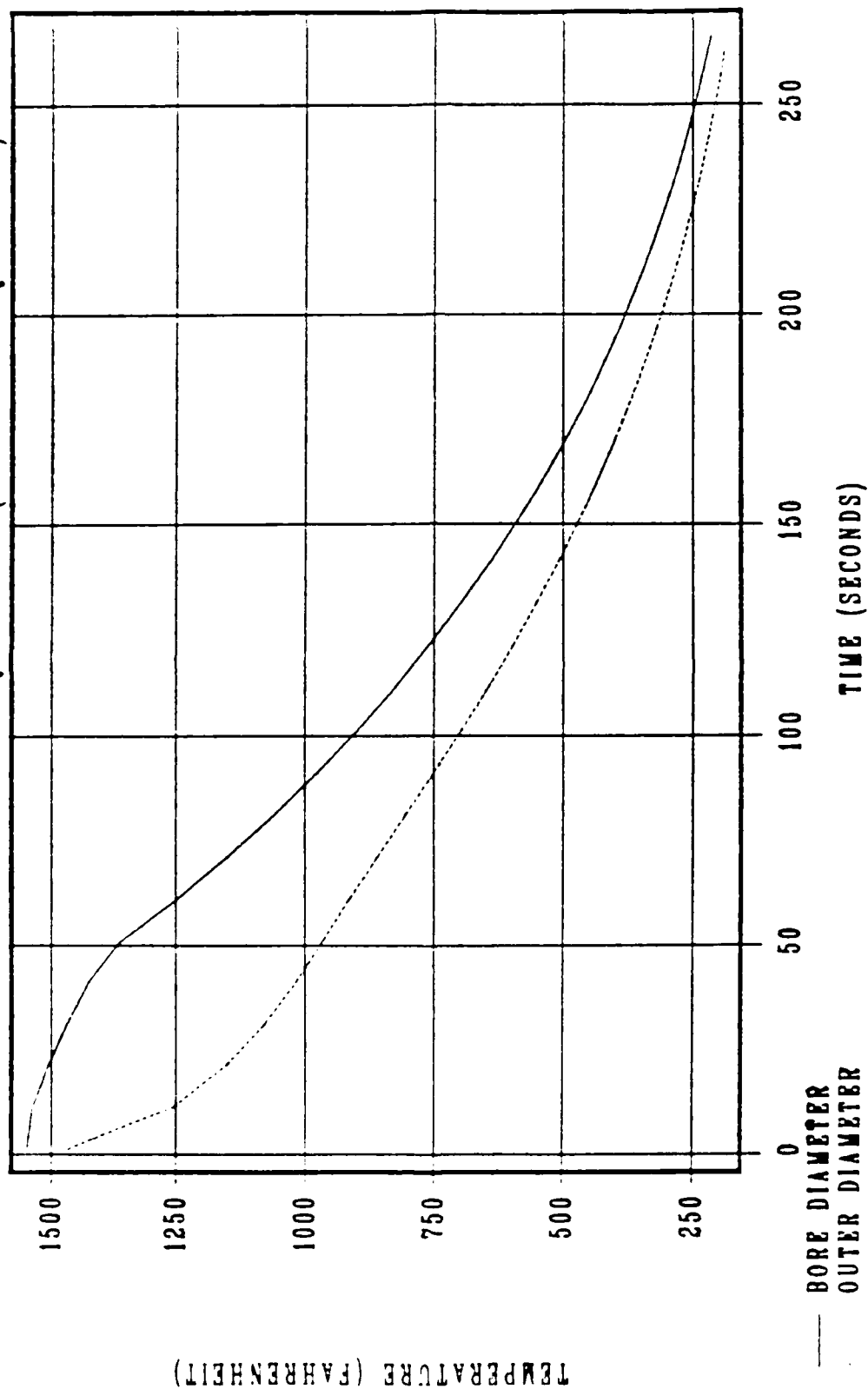


FIGURE 6.

BORE AND OUTER SURFACE TEMPERATURE HISTORY DURING QUENCH (NO BORE QUENCH)



PAST QUENCH CYCLE
(10/5/84)

FIGURE 7.

TRANSIENT TEMPERATURES IN TUBE DURING QUENCH

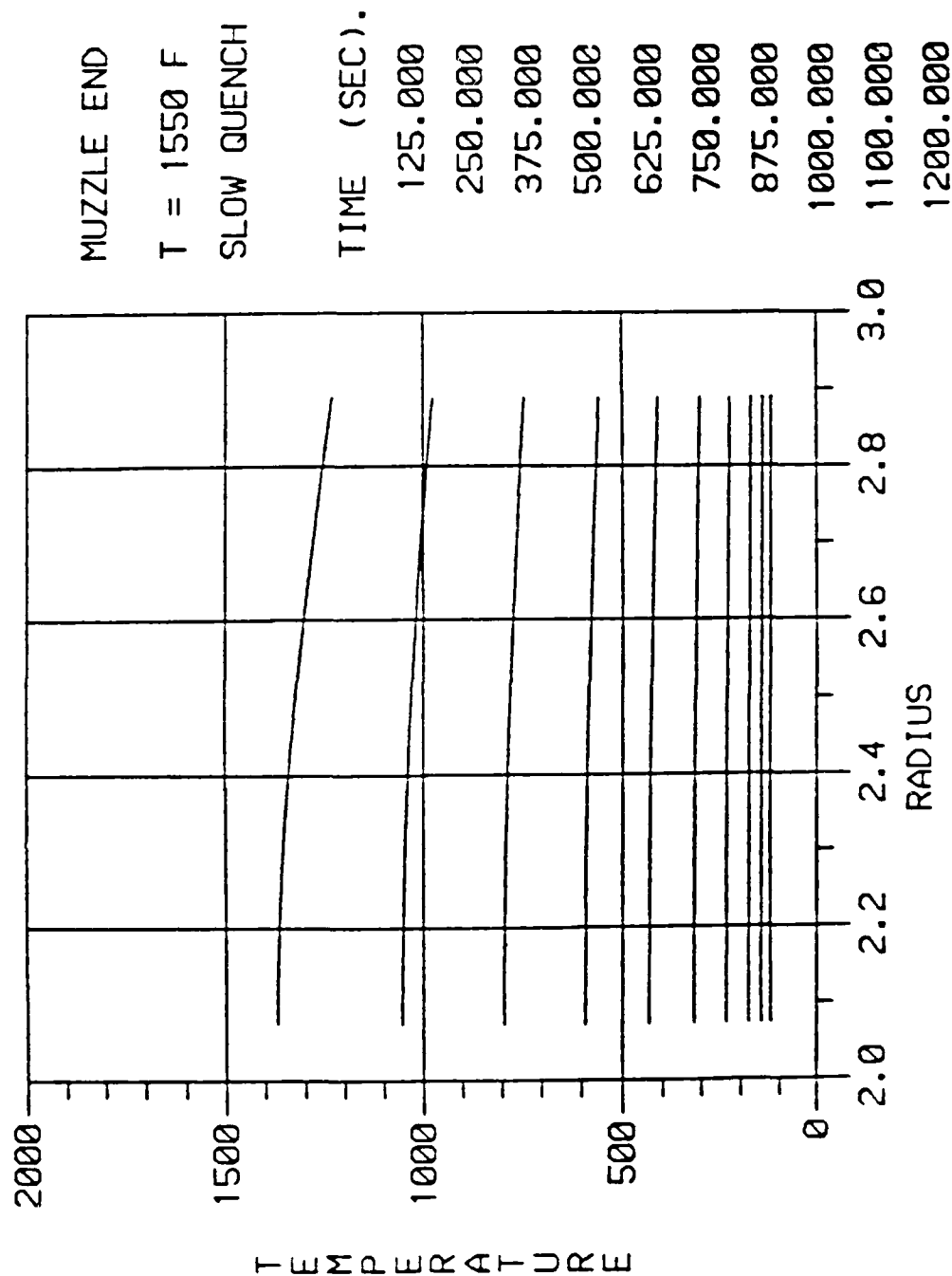


FIGURE 8.

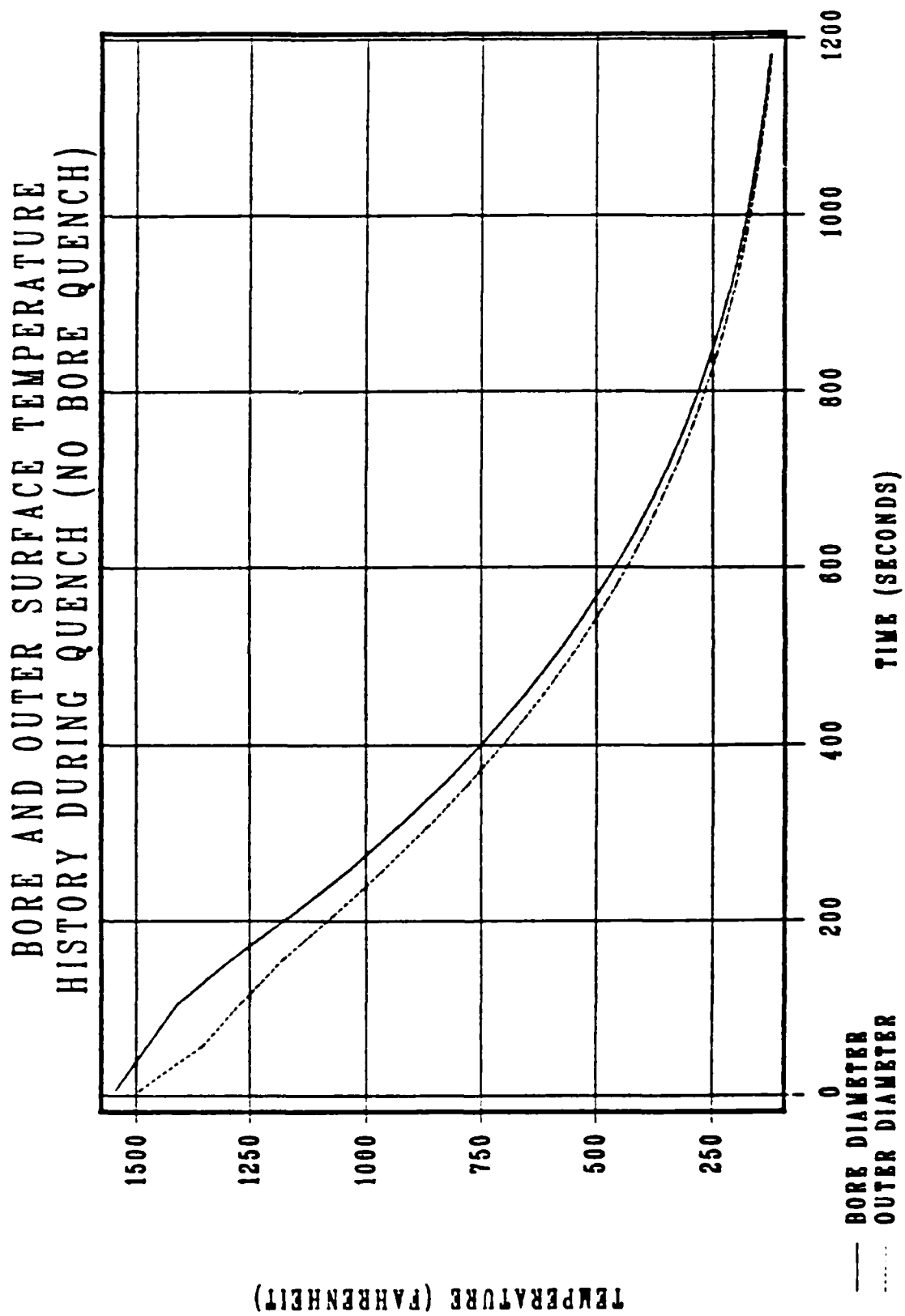


FIGURE 9.

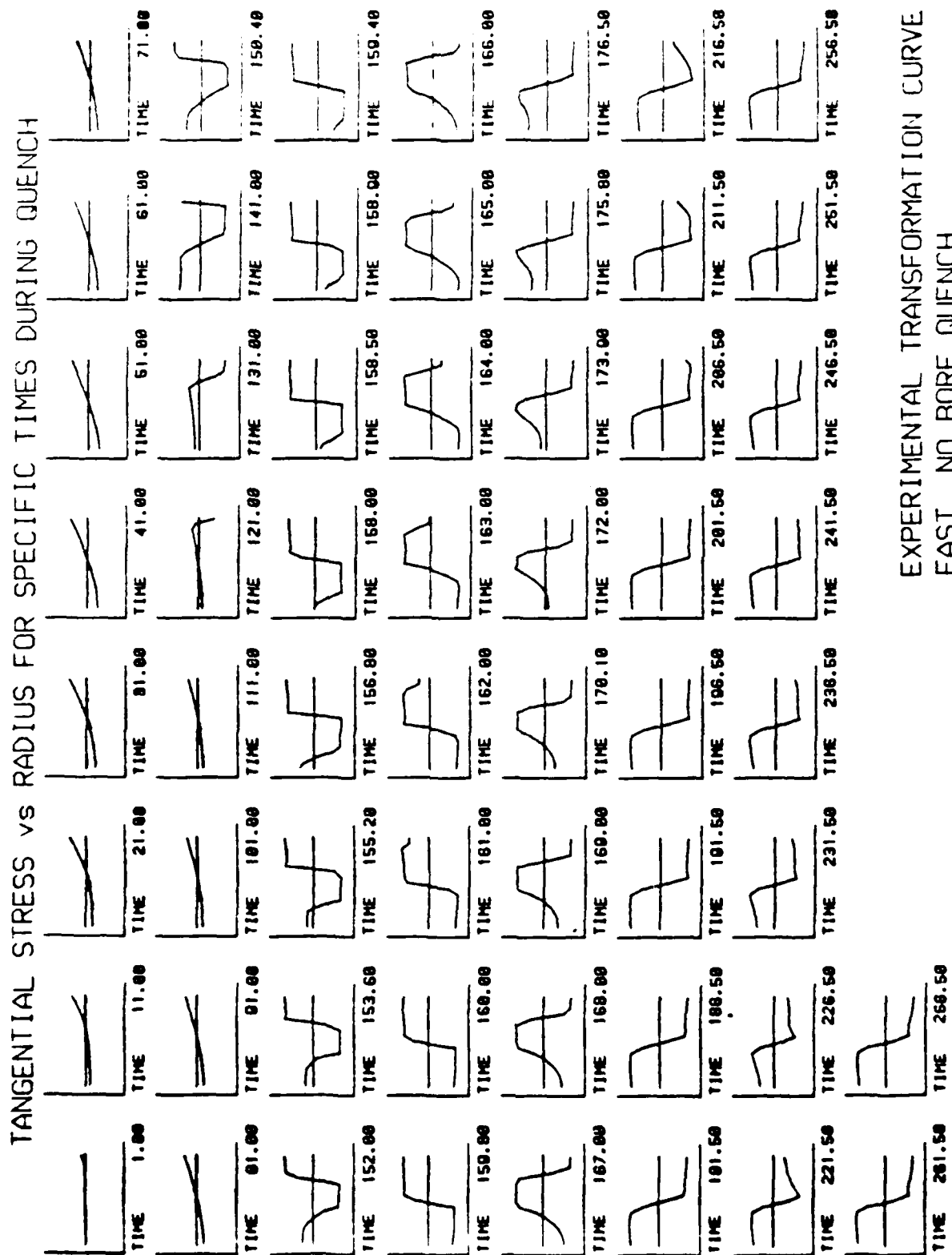
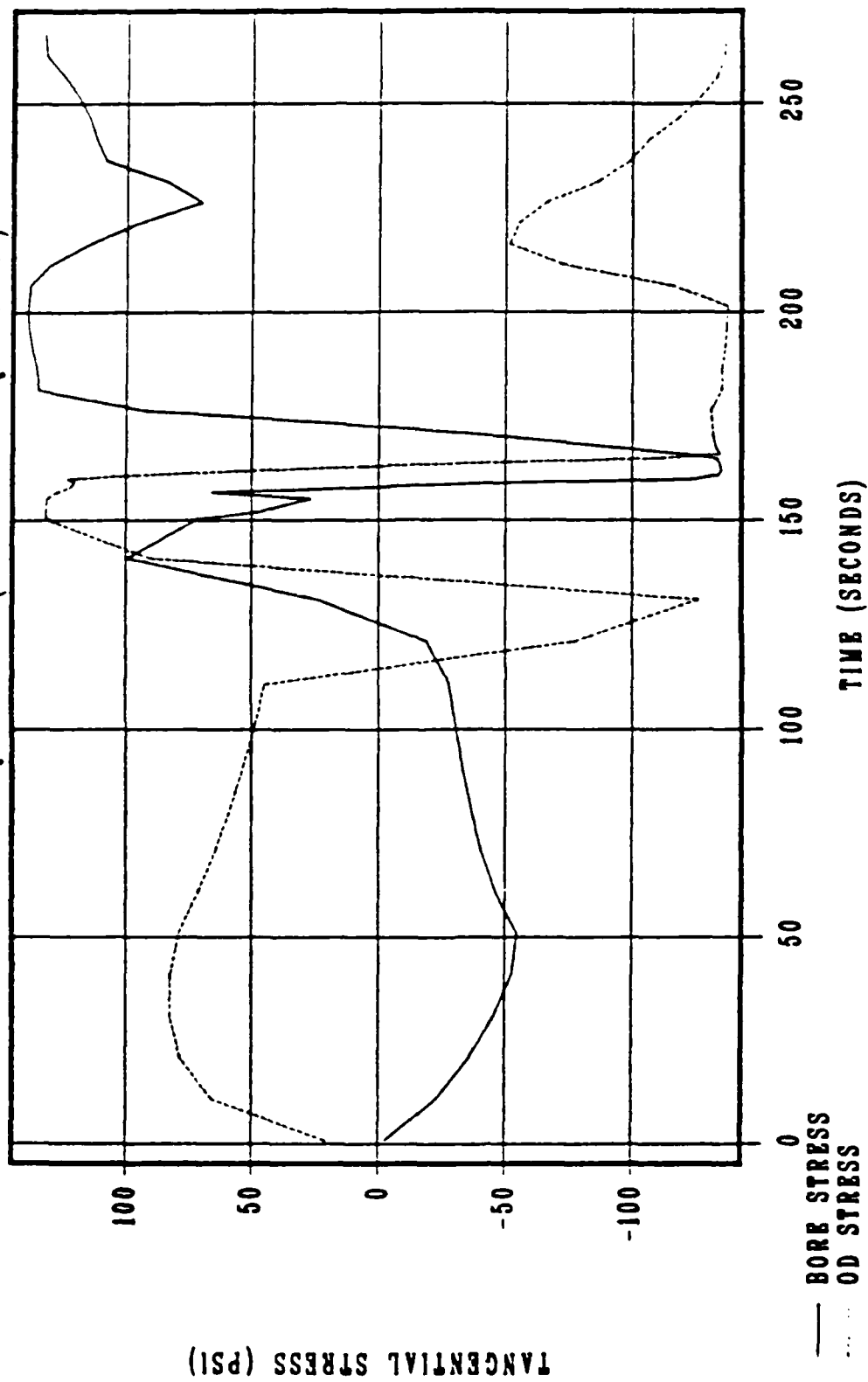


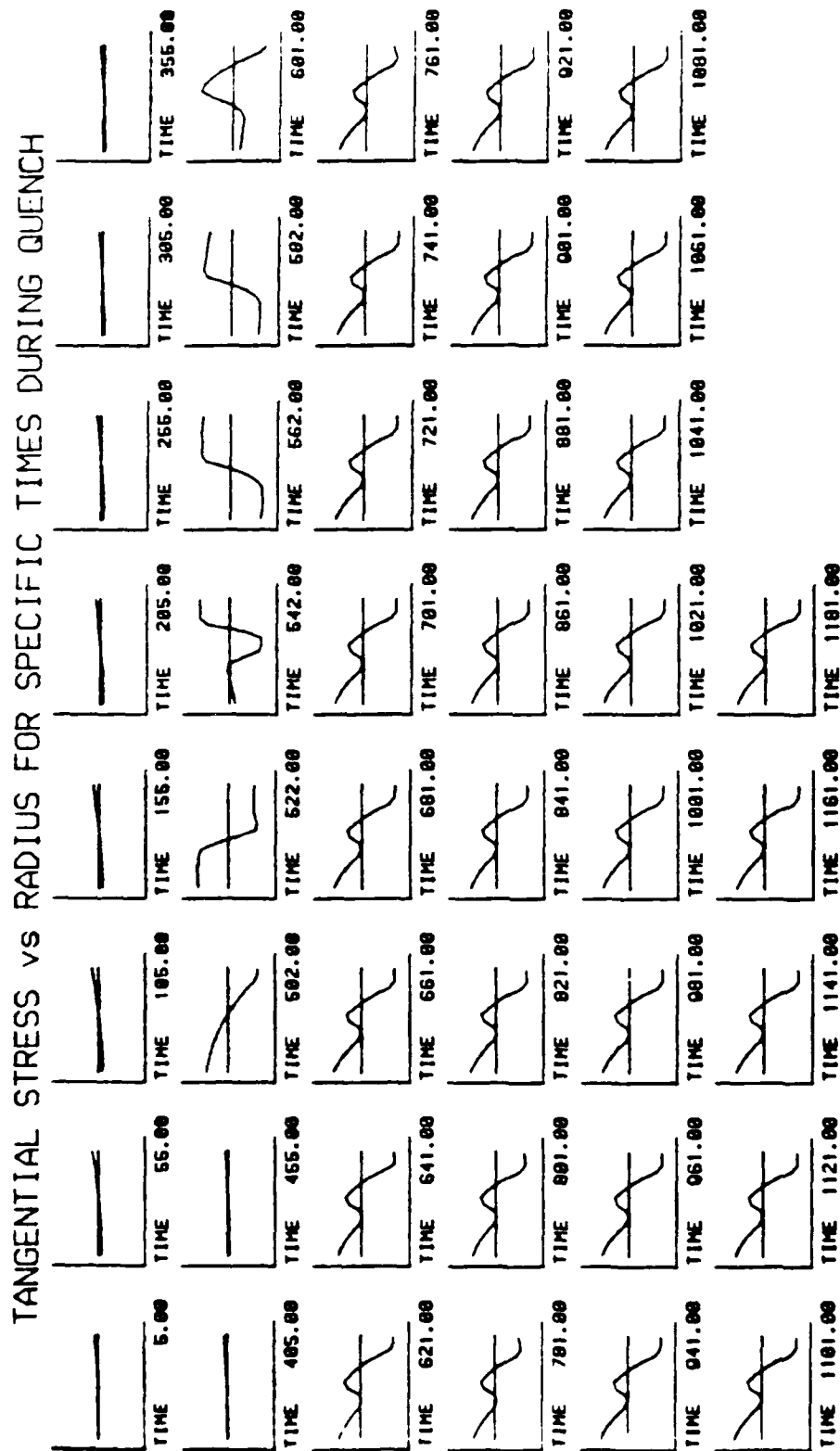
FIGURE 10.

THOUSANDS THERMAL AND TRANSFORMATION STRESSES DURING QUENCH (NO BORE QUENCH)



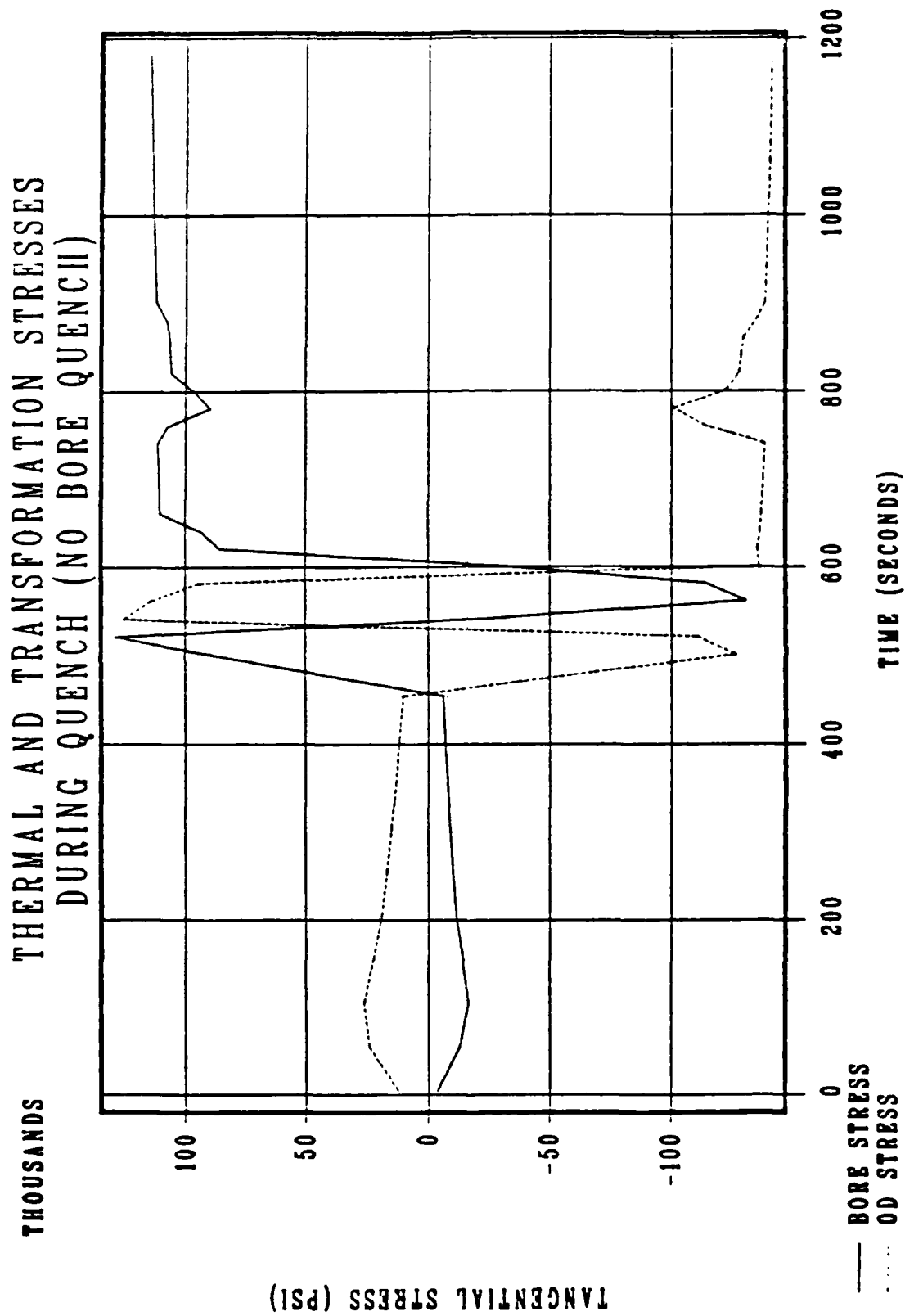
BASED ON EXPERIMENTAL
TRANSFORMATION CURVE
(FAST QUENCH) 12/31/84

FIGURE 11.



EXPERIMENTAL TRANSFORMATION CURVE
SLOW, NO BORE QUENCH

FIGURE 12.



BASED ON EXPERIMENTAL
TRANSFORMATION CURVE
(SLOW QUENCH) 12/31/84

FIGURE 13.

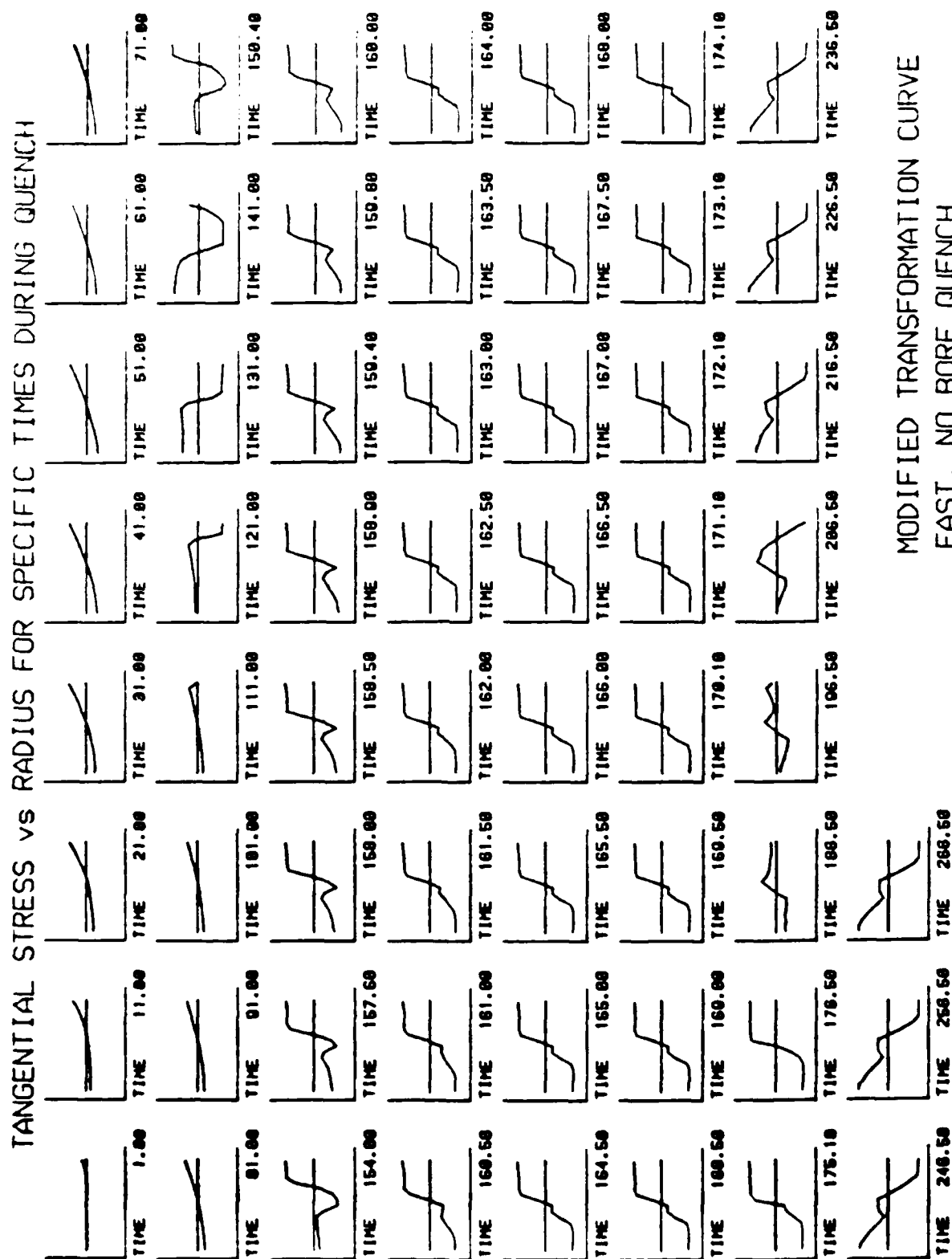
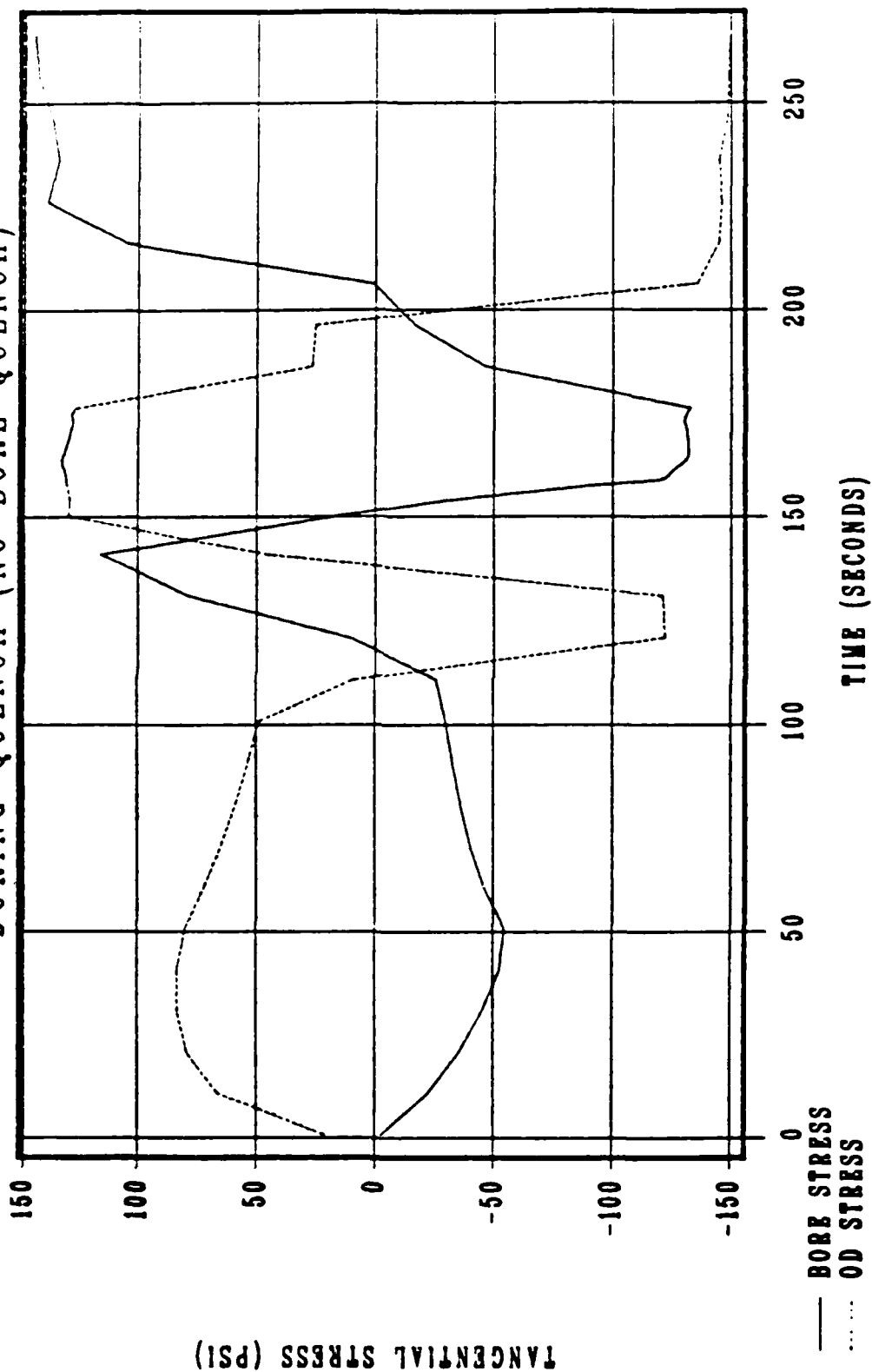


FIGURE 14.

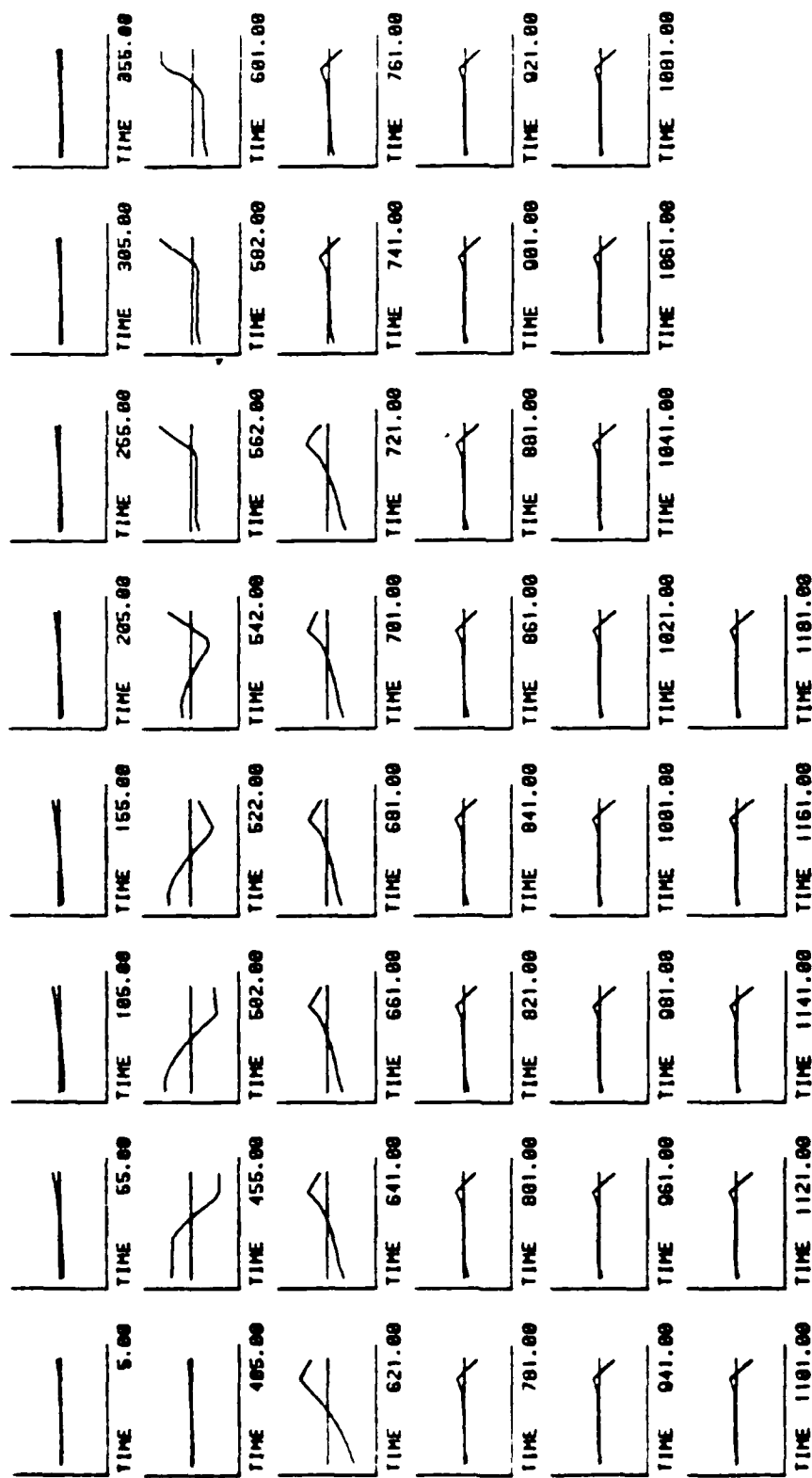
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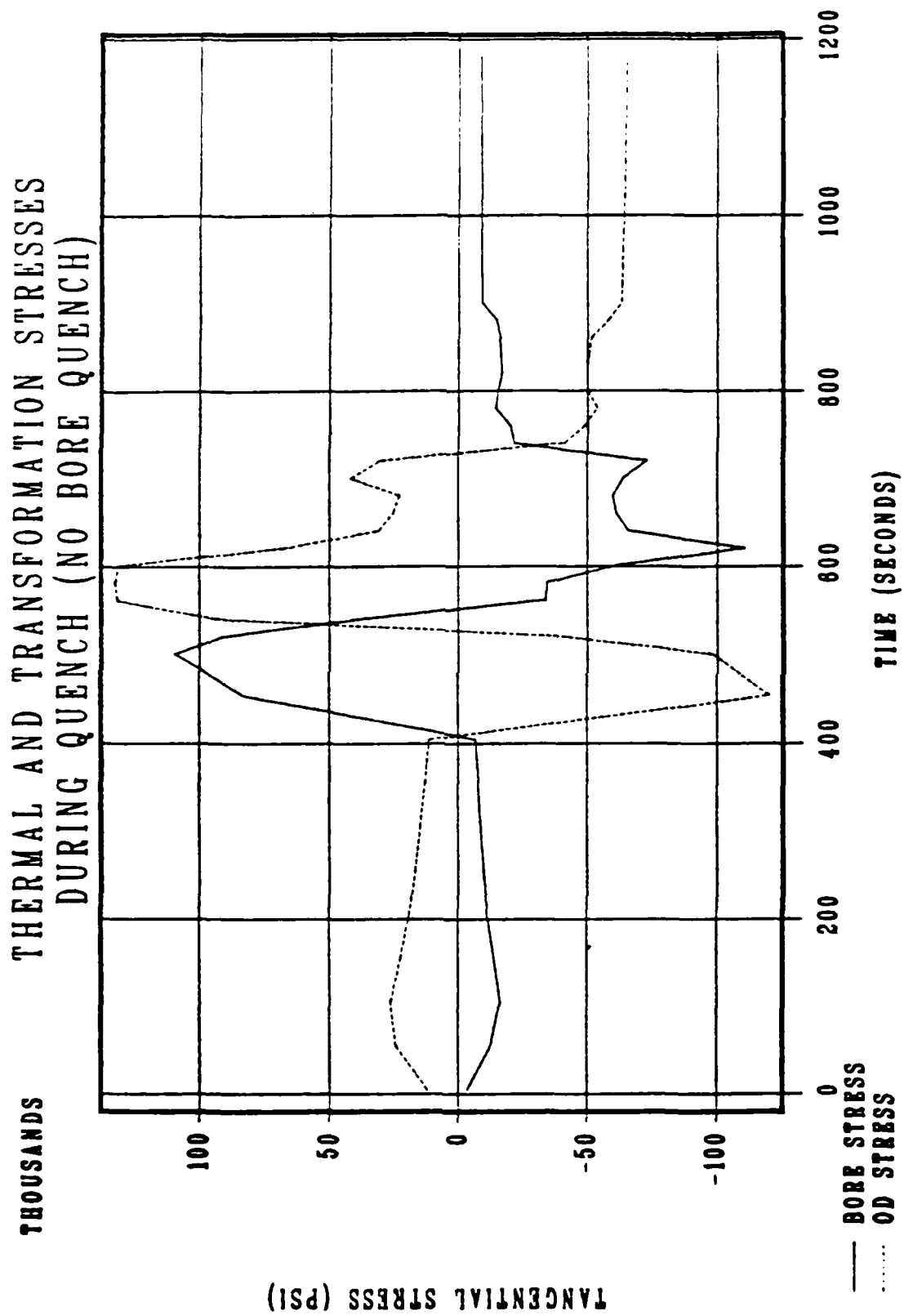
FIGURE 15.

TANGENTIAL STRESS vs RADIUS FOR SPECIFIC TIMES DURING QUENCH



MODIFIED TRANSFORMATION DATA
SLOW, NO BORE QUENCH

FIGURE 16.



BASED ON MODIFIED
TRANSFORMATION CURVE
(SLOW QUENCH) 12/31/84

FIGURE 17.

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